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Ethanol in gasoline: environmental impacts and sustainability review article

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Abstract

This study concerns the use of ethanol as a gasoline (petrol) additive, at levels around 10% by volume ('E10') as well as an 85% blend ('E85'). By detailed reviews of the peer-reviewed and technical literature, five environmental aspects of ethanol enrichment are examined: (1) its purported reduction in air pollutant emissions; (2) its potential impact on subsurface soils and groundwater; (3) its purported reduction in greenhouse gas emissions; (4) the energy efficiency of ethanol; and (5) the overall sustainability of ethanol production. The study indicates that E10 is of debatable air pollution merit (and may in fact increase the production of photochemical smog); offers little advantage in terms of greenhouse gas emissions, energy efficiency or environmental sustainability; and will significantly increase both the risk and severity of soil and groundwater contamination. In contrast, E85 offers significant greenhouse gas benefits, however it will produce significant air pollution impacts, involves substantial risks to biodiversity, and its groundwater contamination impacts and overall sustainability are largely unknown.

Keywords: Gasoline; Ethanol; Energy; Groundwater; Air pollution; Environmental management

Contents

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1. Introduction

Since their introduction one to two decades ago, gasoline oxygenates such as methyl tertiary-butyl ether (MTBE) and ethanol have been mired in controversy. For example, over the past 2 years there has been a widespread public controversy in Australia over the sale of ethanol-enriched unleaded gasoline (petrol). During 2002, press reports revealed that gasoline was being sold at levels in excess of 10% ethanol by volume, and in some cases higher than 20%, in particular by independent retailers in Sydney and Wollongong, without any labeling to indicate this fact [1–3]. The problem arose from the lack of regulation of the ethanol content of gasoline or labeling under Australia's fuel quality regulations [4]. Following a protracted (and damaging) public debate, which mainly focused on the potential damage to car engines and components, the Australian Government announced that it would limit the ethanol content of gasoline to 10%, taking effect on 1 July 2003 [5]. This threshold was selected despite evidence that possibly a third of Australia's cars will not operate satisfactorily on a 10% ethanol blend [6]. Subsequent to this decision, the major oil producers in Australia have largely avoided retailing ethanol-enriched gasoline, due to the poor public relations image of ethanol-enriched blends, although one producer is retailing a 10% ethanol blend through a subsidiary brand at five trial sites in one state [7]. However, the Australian government has also announced a production target of 350 million litres (ML) of biofuels (both ethanol and biodiesel) by 2010 [8,9]. Moves are afoot by some parties, especially ethanol producers and farming interests, to make the 10% ethanol in gasoline mandatory [10]. Although Australia does not mandate the oxygen content of gasoline, and has largely avoided the use of MTBE as a gasoline additive, the political dimensions of the ethanol-in-gasoline debate are broadly similar to the US [11,12] and Canada [13].

Proponents of ethanol enrichment, in Australia, North America and Europe, make three main environmental arguments: (1) a purported reduction in air pollutant emissions during combustion; (2) a purported reduction in greenhouse gas emissions and dependence on

fossil fuels; and (3) the 'sustainability' of ethanol production, by closure of the carbon cycle. However, one oft-overlooked aspect of the ethanol debate is (4) the potential impact of ethanol-enriched gasoline on subsurface soils and groundwater. Recent studies, especially in the US, indicate that ethanol-enriched gasoline has a greater impact on groundwater than unadulterated gasoline, even at an ethanol level of 10%, due to a variety of effects (to be examined shortly). There has also been a longstanding debate over the air pollution benefits of ethanol. Furthermore, there is considerable controversy over (5) the energy efficiency of ethanol, taking account of the energy required for its manufacture.

The aim of this study, then, is to attempt to clarify the ethanol enrichment debate, by examining the entirety of this topic, with particular attention to issues (1)–(5). Since so much is unknown—especially when applied to countries such as Australia—it is not always possible to summarize the 'facts'; for this reason the study proceeds by posing a series of questions, many of which require further research. The study mainly concerns environmental impacts, based on a comprehensive review of the peer-reviewed technical literature since the mid-1980s, and many government or privately commissioned research agency and company reports. Although the study makes specific reference to the Australian experience, the review is quite broad and applicable to most other industrialized countries, at least in moderate temperate to tropical climates. The study is restricted to ethanol enrichment of unleaded gasoline (unleaded petrol), and does not examine heavy vehicle fuels such as diesel and biodiesel, although these are an important (separate) environmental issue. The study mainly concerns 10 vol.% (3.5 wt%) ethanol in gasoline (E10), and close variants such as 15 and 20% blends (E15 and E20). Non-oxygenated (neat) unleaded gasoline is referred to as 'E0'. Reference is also made to an 85% ethanol fuel (E85), used in ethanol-fuelled and certain hybrid vehicles. The present study expands upon an analysis initially presented to the Enviro 04 conference, Sydney, Australia [14].

2. Q1: Does ethanol enrichment reduce air pollutant emissions?

One of the primary arguments of ethanol enrichment advocates is the claimed reduction in air pollutant emissions by E10, relative to E0 [10,11]. Ethanol is an 'oxygenate'—so the argument goes—and thus introduces greater oxygen to the fuel mixture, improving the efficiency of combustion [10,11]. However, the true picture is far more complex than this simplistic argument might suggest. Based on a considerable number of studies of vehicle (and other engine) tailpipe emissions and fuel life cycle analyses in the peer-reviewed and technical literature [15–48], the evidence indicates that:

- E10 generally produces lower tailpipe emissions of total hydrocarbons and carbon monoxide (CO) than E0, with some instances of comparable or higher emissions [17,18,20–22,24,26,27,30,37,39–41,43,44]. These trends are also observed with E20 [45,46].
- E10 causes a significant to substantial increase in emissions of acetaldehyde (ethanal), with levels increasing by about 100–200% [17,18,20,22,26,27,29,31,37,42,44] and in some cases by up to 700% [22]. One study indicated lower emissions with E10,

but higher emissions with E15 [41]. Large increases in acetaldehyde emissions are also observed with E20 [46]. Note that acetaldehyde is a hazardous compound and probable carcinogen [49,50]. Acetaldehyde is also a precursor to peroxylacetate nitrate (PAN), a respiratory irritant with acute toxicity, and a known plant toxin [31,51].

- E10 also causes substantial increases in ethanol emissions, as might be expected, both by tailpipe emissions and evaporative losses [29,37,42,44].
- E10 is generally observed to cause higher emissions of nitrogen oxides (NO_x) than E0 [17,24,26,27,30,40], with some studies indicating mixed results [21,22,44] and/or similar or lower emissions [18,22,39]. One Australian study indicated a 0.5% decrease for pre-1986 vehicles, and a 5.0% increase for post-1986 vehicles [8,27]. Note that NO_x are a key precursor to the formation of ground-level ozone (O_3), and thence of photochemical smog. NO_x emissions exhibit a strong dependence on the fuel–air ratio [40,44], implying that engine optimization for E10 might be required. Two studies on E20 variously indicated lower NO_x emissions than E0 [45] or substantially higher emissions [46]. Longer-chain alcohol additives (propanol to pentanol), at 10% by volume, each also increase NO_x emissions [32].
- Considering other hazardous air pollutants:
  - E10 has been variously observed to reduce 1,3-butadiene emissions relative to E0 [18,20,27], have a minor effect [37] or give mixed results [22].
  - E10 has been found to increase formaldehyde emissions [18,20,27], give mixed results [22] or reduce emissions [41]. Formaldehyde emissions were found to exceed E0 with E15 [41], but were similar or lower with E20 [46].
  - E10 is generally observed to reduce benzene emissions [17,18,20,22,26,27,37,41] with increases in some instances [22]. Benzene emissions are strongly correlated with the benzene, substituted aromatic and (to a lesser extent) cyclohexane content of the fuel [29].
  - E10 has been found to reduce toluene and xylene emissions [27,37,41].
  - E10 has been observed to increase acrolein emissions [8,27].
  - Both ethanol and MTBE increase methanol emissions [29].
  - E10 has a minor effect on acetone emissions [37].
  - Emissions of ethylene in many instances increase with E10 [37].

  Tests on E20 indicated lower benzene, toluene and hexane emissions relative to E0, with mixed results for 1,3-butadiene and xylenes and unchanged formaldehyde [46].
- Based on the above data, the tailpipe emission performance of E10 is quite different to that of MTBE gasoline, which has been shown to produce significantly to substantially lower tailpipe emissions of CO, volatile organic compounds (VOCs), benzene, acetaldehyde, 1,3-butadiene, and lower to slightly higher NO_x emissions, but with higher formaldehyde emissions [17,30].
- E10 has been found to produce lower particulate emissions than E0 [15,21,27]. Particulates increase substantially with decreasing temperature [21]. In two old studies, the mutagenicity of the particulates decreased with E10 [15], but the particulate composition was largely unchanged [16].
- A catalytic converter, when present, is usually more important in reducing emission levels than the fuel composition [37,41]. Ethanol and to a lesser extent acetaldehyde are quite resistant to breakdown in the converter [37].

- Most vehicles have higher emissions than those measured in standard laboratory emissions tests [47]. Of concern are so-called 'super emitters', individual vehicles which emit many times normal emissions [30,47]. The emissions benefits of E10 are greater for older or higher emitting vehicles [48]. One Australian study revealed roughly a half to one order of magnitude difference in emissions of most air toxics between pre-1986 and post-1986 vehicles, for both E0 and E10 fuels [8,27], implying that the elimination of pre-1986 vehicles would offer much greater benefits for air quality than the introduction of E10.
- Ethanol is an octane booster, enabling it to be used as a substitute for tetraethyl lead in those nations which still use leaded gasoline [52].

Tests on a two-stroke chainsaw engine using E15 confirm several of the above trends, with substantial increases in acetaldehyde emissions, and increases in formaldehyde and NO_x emissions relative to E0 [38]. However, total hydrocarbon and CO emissions actually increased [38], as did emissions of several aldehydes including propanal, benzaldehyde and tolualdehydes [38]. Tests of two-stroke and four-stroke outboard engines with E20 indicated lower hydrocarbon and CO emissions, but higher (with four-stroke, substantially higher) NO_x emissions [19].

In addition to tailpipe emissions, fuel evaporative losses are a major concern. Low-ethanol blends such as E10 and E20 have a higher Reid vapor pressure (RVP) than E0 above about 16 °C, producing higher evaporative losses [8,30,37,46], of the order of 20–80% higher than E0 [24,27,30,31]. Permeation rates of E10 through a range of polymer materials are substantially higher than E0 [53]. One study suggests that diurnal evaporative losses are related to the fuel RVP, whilst hot soak emissions (produced during engine cooling) are related to the fuel's distillation characteristics [8,27]. Including the effect of evaporative losses, E10 was found to increase total hydrocarbon, non-methane organic species and air toxic emissions [24,30], substantially increasing the ozone forming potential relative to either MTBE gasoline or E0 [24,25,30]. The co-mingling of E10 and E0 in vehicle fuel tanks, in markets in which both products are retailed, leads to substantial increases in RVP, and is a matter of concern [8,24,31]. In contrast, evaporative losses from MTBE gasoline are low [30].

A total emissions model of the South Coast airshed, California, including the effect of evaporative losses, predicted lower CO emissions than E0, similar NO_x, 1,3-butadiene and formaldehyde emissions, but higher benzene, acetaldehyde and ethanol emissions [31]. A recent review confirms these trends, with a E10 offering a clear air quality benefit over E0 only for CO and 1,3-butadiene, with clear risk of higher acetaldehyde and PAN [48]. For these reasons, the state of California attempted to appeal the USEPA summertime gasoline oxygenate requirement [54]. The problem has since been handled in the US by strict controls on gasoline volatility, requiring modifications to the composition of fuels blended with ethanol [31,36]. In the Australian context, it should be noted that no controls on the RVP of ethanol-gasoline blends are proposed under forthcoming Australian fuel quality regulations, and the regulation of RVP will be left to the States and Territories [4,55]. The author could not identify any

Australian modeling studies which include the effect of evaporative losses, despite the importance of this issue.

The evidence therefore suggests that E10 produces lower total hydrocarbon, CO, benzene and particulate tailpipe emissions than E0, and possibly lower 1,3-butadiene emissions, but at the expense of substantially higher acetaldehyde and ethanol emissions, and higher NO_x, methanol and ethylene emissions. There is mixed evidence regarding formaldehyde emissions. However, evaporative losses from E10 are substantially higher than E0 above about 16 °C. Unless special measures are taken to reduce the volatility of E10, many of its emission benefits (total hydrocarbons and air toxics) are reversed, and its ozone forming potential is significantly enhanced. In this regard, the potential increases in NO_x and ethylene emissions by E10 (even without RVP control) are of concern, as both play a major role in ozone formation [37].

Two Australian life cycle analyses of E10 by the CSIRO, which include the effect of embodied emissions (generated by production and transport of the ethanol), indicated generally lower total hydrocarbon and CO emissions than E0, slightly lower to higher NO_x emissions, and similar to significantly higher particulate emissions, depending on the choice of ethanol feedstock [8,36]. However, the life cycle models do not appear to include evaporative losses, and may therefore substantially underestimate total emissions from E10. One study [36] also suggests that E10 has lower total air toxic emissions than E0; however, the modeling of air toxics appears to be based on California reformulated (i.e. MTBE) gasoline, and not specifically on E10 [compare Ref. [36], Table 14.10; and Ref. [34], Table S2].

E85 has been found to produce substantially greater acetaldehyde (by up to 27 times) and formaldehyde emissions than E0, but substantially lower benzene and lower VOC and 1,3-butadiene emissions [23,28,33–35]. Total tailpipe air toxic emissions ranged from being lower to higher than E0 [33–35]. Tailpipe hydrocarbon, CO and NO_x emissions are comparable to or lower than E0 [18,23]. Vehicle particulate matter emissions are comparable to E0 [47] or higher [23]. E85 has a lower vapor pressure than E0, causing lower evaporative losses [47]. However, fuel life cycle analyses, including embodied emissions, indicate that total VOC and CO emissions from E85 are substantially higher than E0, whilst total NO_x and particulate emissions are comparable to or significantly higher [33,36,47]. (For example, the burning of sugar cane fields prior to harvest causes significant particulate emissions.) Lifecycle total hydrocarbon emissions are lower to significantly higher than E0 [36], whilst total air toxics are about the same [47]. The ozone potential is slightly better than E0 [47].

Several ethanol-fuel air quality case studies are presented in the literature. In Brazil, the only nation to implement a large-scale ethanol fuel program, about 70–75% of vehicles are fuelled by E20–E24 gasoline, 15–20% (and falling) by pure ethanol, and the rest (mainly heavy vehicles) by diesel [56,57]. A 2001 study of ambient air concentrations in Sao Paulo, Brazil, reported ethanol levels 23–78 times those measured in Los Angeles, whilst levels of propanol and various *n*-aldehydes (butanal to nonanal) were about 10 times higher [56]. Levels of benzene, toluene, ethylbenzene and xylenes (BTEX) were somewhat higher than LA—but compare favorably with Asian cities (Bangkok and Manilla)—whilst alkane levels (butane to undecane) were comparable [56]. In four major Brazilian cities, reported acetaldehyde levels (1.9–48 ppb) are substantially higher than

those elsewhere in the world, whilst formaldehyde levels (1.3–52 ppb) are slightly higher [31,57,58]. Such levels have been attributed to the lack of Brazilian control on fuel RVP, and thus to higher evaporative losses, rather than to strictly tailpipe emissions [31]. Levels of both aldehydes have fallen by about 50% since the early 1990s, attributed to fleet turnover and the mid-1990s cessation of sales of pure ethanol vehicles [31,57].

In the US, oxygenated gasoline (2–3.5 wt% oxygen) is mandated by Federal regulations in several jurisdictions, during winter months to combat CO and/or during summer to combat ozone [31]. In the Denver metropolitan area, subject to a winter CO mandate, measured formaldehyde and acetaldehyde levels did not differ significantly between the winters of 1988/89 (mainly MTBE) and 1995/96 (mainly ethanol) [59]. However, formaldehyde levels increased significantly when the oxygen content was raised from 2.0 to 2.6 wt% [60]. A study of Albuquerque, NM, found a 10% increase in acetaldehyde levels one winter, but a fivefold decrease in another (both mainly E10), relative to a summer reference (mainly E0) [61]. An interesting analysis of nationwide USEPA monitoring data, to identify the number of times the ozone air quality standard has been exceeded, indicate that exceedences increased significantly between 1993–1994 and 1995–1996 (33–53%) in districts using E0, and generally decreased (−34 to 4%) in districts using mainly MTBE gasoline, but increased substantially (78–119%) in districts using mainly E10 [62,63]. Such high increases were attributed to the higher NO_x emissions of E10; higher E10 permeation through vehicle components; and higher VOC tailpipe emissions due to poorer driveability [62]. A Wisconsin study indicated average winter 8am CO levels fell by 0.56 and 0.26 ppm in E10 and E0 areas respectively, whilst summer CO levels were the same [64]. There was concern over a predicted increase in summer VOC levels, and possibly in ozone levels.

On the balance of evidence, it appears that E10 may offer some advantages over E0 in reducing particulate and CO emissions, and (with RVP control) in reducing total hydrocarbon and air toxic (especially benzene) emissions. However, without RVP control (and possibly even with it), total hydrocarbon and air toxic emissions may be higher than E0 due to evaporative losses. In addition, the life cycle emissions of hydrocarbons, CO and particulates may negate the vehicle emission benefits. Even with RVP control, E10 is known to cause substantially higher acetaldehyde and ethanol emissions, and higher NO_x emissions and permeation losses, all contributing to a higher ozone potential of E10. A study of US monitoring data tends to verify this conclusion, revealing an association between E10 and substantial increases in ozone levels. In Australia, in which many cities experience episodic ozone levels close to or in excess of air quality standards [65], and in which RVP control has been left to the States and Territories, such effects should viewed with great concern. In accordance with the precautionary principle, the introduction of E10 must be approached with great care, as it may actually cause harm rather than good. Much more research, case study evidence and air quality modeling of specific districts is needed on this issue.

3. Q2: What is the impact of ethanol enriched gasoline on soil and groundwater contamination?

In many industrial nations, groundwater is an important, well-established water resource both for private homes and for reticulated water supplies. Although not widely used in Australian cities (except Perth), groundwater is increasingly being seen as an important water resource, especially given Australia's recurring droughts. Protection of this water resource is therefore paramount, for ourselves and for future generations. In this context, it must be recorded that many studies indicate that ethanol-enriched gasoline has a greater impact on soil and groundwater than E0, due to a variety of effects [66–81]. To summarize the evidence:

- In contrast to gasoline, which is an electrical insulator, ethanol and ethanol-enriched gasoline conduct electricity [69,82]. Ethanol-gasoline also undergoes a phase separation on contact with water, with ethanol reverting to the aqueous phase, increasing its volume [83]. These effects can increase the corrosion of steel underground storage tanks, increasing the risk of leakage to surrounding soils.
- In addition to leaks from underground storage tanks, a significant proportion of leaks at service stations occur from the underground fuel feed lines, pump stations, fill points, fittings and other components [84]. As with the components in car engines, these are not necessarily designed for ethanol-enriched fuel mixtures. In particular the US Center for Transportation Research [85] advises: "Aluminum, zinc, tin, lead-based solder, or brass fittings should not be used with pure ethanol or gasoline with high percentages of ethanol. When in contact with liquids that contain high percentages of ethanol, some nonmetallic materials also degrade, including natural rubber, polyurethane, cork-gasket materials, leather, polyester-bonded fiberglass laminate, polyvinyl chloride, polyamides, and methyl-methacrylate plastics." Such effects are generally not significant with E10 [83] but become important with E20 [46]. However, they could occur with E10 if pockets of phase-separated ethanol-water develop. The higher permeation rate of E10 through polymers has also been noted [53]. The use of such materials for the storage and handling of ethanol-enriched fuels increases the potential for material penetration or failure, increasing the risk of leakage to surrounding soils.
- Ethanol reduces the interfacial tension of gasoline with respect to water, which falls from 71 to 46 to 40 $\mathrm{mN\,m^{-1}}$ from E0 to E10 to E20 [78,81]. This enables the ethanol-gasoline non-aqueous phase liquid (NAPL) to enter smaller pore spaces, and to infiltrate more easily through the vadose zone to the water table [69,72,78]. The effect is complicated by strong ethanol partitioning to vadose zone water, which significantly reduces ethanol transport to the water table [72,78,79]. Although suspected [69], no significant changes to NAPL spreading on the capillary fringe or water table are observed in small-scale experiments, attributed to the loss of ethanol before the fuel reaches the water table [78,79]. Of course, large-volume E10 (or pure ethanol) spills could overcome this effect and reach the water table, increasing NAPL spreadability.
- Alcohols are known to cause the dehydration of both swelling and non-swelling clays, producing microfractures which increase the clay permeability [69,86].

- Once in contact with groundwater or surface waters, the presence of ethanol increases the solubility of petroleum constituents in the water [67–69,87]. This has several effects:
  - It increases the solubility of the more hazardous, monoaromatic constituents of gasoline such as benzene, toluene, ethylbenzene and xylenes (BTEX) [67–69]. Studies indicate that E10 increases the solubility of BTEX compounds by anywhere from 30 to 210% [74,87]. This effect is limited to the early stages of a spill, before the ethanol fractionates into the aqueous phase, but nonetheless can produce significant increases in dissolved BTEX [69,72,74]. At higher ethanol concentrations, the enhanced solubility is quite pronounced, and there is great concern over groundwater protection at bulk ethanol terminals and gasoline blending facilities [69,72].
  - If a high-ethanol release encounters older, residual (ethanol-free) NAPL—for example at terminal sites—the NAPL itself can be remobilized by contact with the ethanol, and flushed from the vadose zone towards the water table [69,75,81].
  - High-ethanol spills can also remobilize sorbed BTEX by dissolution [72].
- Ethanol inhibits the biodegradation of petroleum contaminants, especially BTEX, by preferential degradation of the ethanol, causing preferential consumption of electron acceptors and nutrients, and changes to microbial populations in favor of ethanol degraders [66,68,69,72,75,76]. Its biological oxygen demand (BOD) also forces more reducing conditions, which can become anaerobic [66] and even methanogenic [75]. These effects work against the ability of the natural environment to restore itself ('natural attenuation'). The net effect is to increase the extent of the dissolved plume of gasoline-contaminated groundwater, particularly of benzene [69,72,75]. Relative to E0, dissolved benzene plume lengths due to E10 are predicted to increase by 7–150% over a 20-year-period [69,70,71,76,77]. Such predictions are borne out by a comparison of gasoline contaminated sites in Iowa (mainly E0) and Kansas (mainly E10), for which the mean length of Kansas benzene plumes was 36% longer (80 ± 31 m) than Iowa (59 ± 41 m) [80]. The median lengths were 80 and 48 m, respectively (69% longer). The mean and median toluene plumes lengths increased, respectively, by 14 and 39%, but were not statistically different.
- No studies on the subsurface impact of E85 were identified, apart from its effect on existing NAPL contamination. Based on its solubility and biodegradability, this fuel blend might be expected to produce a significant but localized solute plume, with BOD and acidity (acetic acid) impacts, possibly with lower collateral problems than E10. More research is required in this area.

In the late 1980s, the USEPA developed the Leaking Underground Storage Tank program to remediate leaking petroleum tanks [88]. Since then, 1.5 million of 2.2 million regulated tanks have been cleaned up, leaving 7,00,000 in service [88]. Stringent regulations on tank and fuel system construction and monitoring requirements were also introduced. However, even with such regulations, leakage problems have not been eliminated [88]. Thus whilst it is possible (and beneficial) to minimize leaks, they can never be prevented. Another consideration is that the dissolution of BTEX from residual NAPL can take of the order of 1 to >10 years, whilst dissolution from NAPL pools can

take $>$10–1000 years [89]. Once NAPL contamination is in place, the groundwater resource can be contaminated for at least one human generation, and possibly much longer.

A complex picture therefore emerges in which E10 increases both the risk and the severity of soil and groundwater contamination [48]. For example, in California, the statewide adoption of E10 is predicted to double the number of drinking water wells affected by benzene [69]. Note that the enhanced risk of E10 relative to E0 is not associated with ethanol itself, but is caused by its impact on other petroleum fuel constituents, and on the behavior of the fuel as a NAPL. As noted, leaks can only be minimized, not prevented, and NAPL contamination can remain in place for decades or centuries. Such considerations must surely obviate the use of E10 as a fuel, except where groundwater impacts are not (nor likely to be) of concern. (A word of caution: many US risk assessments in favor of E10 all use MTBE-adulterated gasoline as the reference fuel, which is of greater concern for its groundwater impact [48,69,72]; this fuel was not widely adopted in Australia). Concerning E85, too little is known of its subsurface impact to make any definitive conclusion.

4. Q3: Will ethanol enrichment reduce greenhouse gas (GHG) emissions?

E10 (and especially E20) is more fuel efficient than E0, but the energy content of ethanol is less than unleaded gasoline [8,22,43,46]. The net effect is a slight increase in fuel consumption with E10, producing a modest increase in tailpipe CO_2 emissions [8,27, 43,46]. When the complete fuel life cycle is considered, including the impact of the production and transport of ethanol, both CO_2 and total GHG emissions by E10 are marginally lower than E0, generally with savings of 1–5% of vehicle emissions [8,36, 90–92]. E20 provides a small (2–11%) benefit [46]. Analyses of the effect of the choice of ethanol feedstock on GHG emissions suggest there is little difference between wheat, molasses, sorghum or wood waste sources [8,36], whilst others suggest wood cropping is highly beneficial [46,47,91]. The discrepancies between models indicate that more work is needed on the model assumptions and input parameters. In all studies, an ethylene feedstock—of fossil fuel origin—causes higher GHG emissions than E0 [36,46].

A recent Australian analysis estimated the cost of GHG abatement by E10 in 2010 to be between A\$265–277/tonne CO_2 [8], equivalent to US\$186–194/tonne at current exchange rates (A\$1 = US\$0.7). The cost of the Brazilian ethanol program is about US\$54/tonne CO_2 [101]. Such figures are substantially greater than the postulated Australian trading value of US\$7–35/tonne CO_2 (A\$10–50/tonne) [93], and recent UK trading prices of US\$8.1/tonne CO_2 equivalent (CO_2e) (UK£4.50/tonne CO_2e, converted at UK£1 = US\$1.80) [94]. For comparison, the cost of CO_2 sequestration in forests is generally in the range US\$3–40/tonne CO_2 [95]. Clearly, ethanol enrichment as a GHG abatement policy is much less cost-effective than other abatement methods, even for a mature ethanol market such as that in Brazil.

Life cycle analyses of E85 or E100 indicate that CO_2 and total GHG emissions are somewhat to substantially lower (19–70%) than E0 [36,47,90,91,96,97]. E85 therefore provides a significant GHG benefit, but its magnitude strongly depends on the ethanol feedstock.

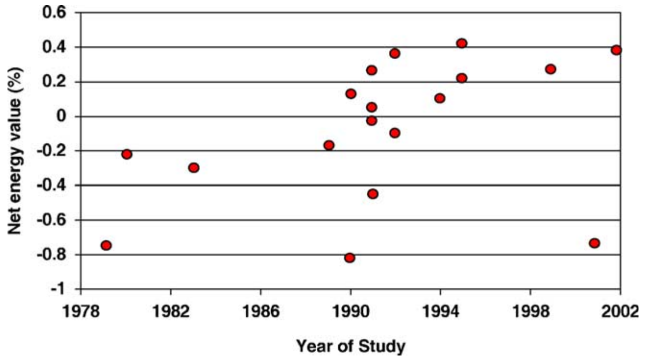

Fig. 1. Net energy value of ethanol as a percentage of its fuel energy, showing results of many studies (redrawn after 62).

5. Q4: What is the energy efficiency of ethanol?

Whilst ethanol contains energy, in life cycle assessment terms its net energy value (NEV) is its fuel energy minus the energy used for its production and transportation. Since the 1970s, a number of calculations of NEV have been presented in the literature [62,98]. The results are plotted on a historical timeline, as percentages of the fuel energy, in Fig. 1. The analyses are sourced mainly from the US, and for the most part reflect ethanol produced from corn.

As evident, the NEV of ethanol is much lower than its energy content, with several studies suggesting it is negative (i.e. the energy used for its manufacture exceeds that released by its combustion). If this were the case, ethanol would not be a source of energy in its own right, but a means of storing energy from other sources; if such sources consist of fossil fuels, then there would seem to be little point in transforming this into ethanol. Needless to say, there has been considerable debate about the implications of these calculations [62,98]. Fig. 1 also indicates an upwards trend of net energy with time, indicating either changes to assumptions made by different modelers, and/or improvements to the ethanol manufacturing process over the past decade [98].

6. Q5: Is ethanol enrichment sustainable?

The Bruntland Commission defines ‘sustainable development’ as that which ‘meets the needs of the present without compromising the ability of future generations to meet their own needs’ [99]. To try to determine whether E10 is more ‘sustainable’ than E0, consider several additional points:

- In every country, fuel ethanol is uneconomic with respect to gasoline, and must be supported by subsidies [8,100,101]. For example, US Federal ethanol subsidies—not

counting state or broader agricultural subsidies—are US$810 million p.a. [100]. In the late 1990 s, Brazil's fuel consumers paid more than US$2 billion/year extra for overpriced gasoline to subsidize ethanol production [101]; a separate study estimated US$100 million/year was transferred to sugarcane farmers as hidden subsidies [102]. The Australian government announced ethanol subsidies of A$37 million in 2003, as well as a 50% excise discount (subsidy) of A12.5c/l until 2011 [9,103]. A separate subsidy of A$444 million for the sugar industry was also announced recently [104]. (Of course, any comparison with E0 must account for the considerable government and military expenditures to protect the oil industry, estimated to be of the order of US$50–250 billion/year [11], although it must be remembered that E10 is 90% gasoline, and would still incur this expenditure.) Efforts are underway to make ethanol price-competitive [105]. Until this occurs, the question remains whether its supporting subsidies would be better expended elsewhere, for example on other sustainability projects.

- The Australian and US ethanol industries are highly concentrated. In the US, the largest firm is claimed to have a 41% market share, whilst the top four firms have a 58% share [62]. Including production capacity and marketing agreements, four companies are claimed to control 95% of supply [62]. The stakes involved are enormous: the US ethanol market grew from 75 million gallons in 1981 to 2.9 billion gallons in 2003, and will yet grow substantially [11,100]. Australia has two ethanol producers, Manildra Pty Ltd and CSR Ltd, of whom Manildra provides 87% of supply [103]. Both US and Australian manufacturers are protected from import competition. Such oligarchical (or monopolistic) industries and restrictions on free trade can only encourage inefficiency and stifle innovation, to the detriment of consumers and long-term societal interests.
- Using existing feedstocks, ethanol production requires large areas of land. For example, mandatory use of E10 in the US (430,000 barrels/day ethanol) would require a 50% increase in the US corn planted area [101]. If made from sugar, mandatory E10 in the US and EU would consume 4.8 times the internationally traded sugar crop [101]. In this vein, the European Environmental Bureau, an association of European non-government organizations, opposed the mandatory introduction of biofuels in the EU, for its threat to biodiversity and continued dependence on agricultural subsidies, for little environmental gain [106].

  In Australia, mandatory E10 would consume the entire sugar crop [107]. Already there is considerable concern over nutrient and pesticide impacts—especially from cane farming—on the Great Barrier Reef along the Queensland coast [108]. The environmental impacts of an increase in the sugar cane farmed area are not known, but based on past experience are likely to be of major concern.

- Ethanol subsidies are but one component of extensive US, European and Japanese agricultural subsidies and import barriers, widely condemned for benefiting mainly rich farmers, increasing taxation, rewarding inefficiency, and denying a livelihood to the world's poorest people [106,109–112]. To place the issue in perspective, total agricultural subsidies in 2001 were: US: US$97 billion (1.0% of GDP), EU: US$99 billion (1.3% of GDP) and Japan: US$57 billion (1.4% of GDP) [113]. Agricultural

subsidies in rich nations fail the first criterion of sustainable development, as they restrict the ability of the present generation (globally) to meet its needs. (Indeed, given the geopolitical uncertainties of the present era, there is a strong argument that the alleviation of poverty worldwide—to achieve greater global political security—is in the best interests of all developed nations; the elimination of all agricultural trade barriers would be a small price to pay towards this goal.) In this respect, the actions of Australia—normally a free trading nation and leader of the Cairns Group of agricultural producers—to protect its ethanol industry, when most other Australian industries are expected to compete on the world stage without subsidies, are quite peculiar.

- To overcome the land problem and develop price-competitive ethanol, new technologies for producing ethanol from cellulose are required, which almost certainly will involve genetic engineering [105,114]. This raises the possibility of tree and/or shrub cropping for ethanol, potentially of great benefit to Australia and many other nations by reversing land clearing and combating dryland salinity [107]. However, as stated bluntly by Hodge [62]: "can we trust the ethanol industry to contain genetically modified or bioengineered bacteria… [with] the potential to literally eat us out of house and home?" Whilst alarmist, given recent experiences with other genetically modified crops such as canola [115,116], it is inconceivable that any such genetically engineered technology could be kept contained over the short to medium term. The development of ethanol-from-cellulose technology therefore involves a significant risk of dramatic—and irreversible—changes to global biodiversity.

The definition of sustainable development requires a focus on the longer term [99]. Application to the ethanol in gasoline issue gives rise to the following ranking of environmental issues (note it reverses the usual human health ranking):

Air pollution (current generation)	<	Subsurface contamination (one-several generations)	<	Global warming (millennia)	<	Loss of biodiversity (irreversible)

Arguably, the (known) subsurface impacts of E10 outweigh any (questionable) air pollution gains. Whether the small GHG benefit of E10 warrants its subsurface contamination impact is also debatable. (This is not to suggest that global warming should be ignored.) The potential biodiversity impacts, due to expanded agricultural activity and/or expanded afforestation, are a moot point. Whilst it is not possible to resolve the question here, the oft-claimed 'sustainability' of E10 relative to E0 is certainly thrown into question. E85 is a different story, due to its substantial global warming benefits, although its air pollution emissions could exceed those of E0, and its subsurface contamination impacts are unknown. There may be a case for E10 production as a transition stage, to encourage technological innovation leading to earlier adoption of E85; however, the potentially considerable biodiversity impacts of ethanol production need to be addressed.

7. Another problem: lack of technical rigor and omissions in many ethanol studies

A final matter worthy of comment is the lack of technical rigor, and in some instances gross inaccuracies, in many published reports and other information on the ethanol-in-gasoline issue. This is unfortunately the case for a number of bulletins and other information published by ethanol producers and their supporters and lobby groups [10–13], in which the detrimental features of ethanol enrichment, and the technical complexities of the issue, are glossed over entirely and/or dismissed without a proper discussion of the facts. A recent petition to the Australian Parliament in support of ethanol enrichment [10], for example, makes several claims such as: "Ethanol contains 35% oxygen. Adding oxygen to fuel results in more complete fuel combustion, reducing harmful tailpipe emissions"; "Ethanol reduces particulate emissions, especially fine particulates…" and that ethanol causes a 'Cleaner environment (lower carbon monoxide and smog-causing emissions)'. Such assertions grossly oversimplify the evidence in the literature (see Section 2): for example, whilst ethanol does reduce tailpipe particulate emissions [15,21,27], total life cycle emissions of particulates are increased significantly [8,36]. Indeed, the final claim is entirely incorrect: there is widespread evidence that E10 actually increases smog-producing emissions, evidenced by higher NO_x emissions [17,24,26,27,30,40], higher evaporative losses [24,25,30] and preliminary case study data [62,63]. In a similar vein, the 'Ethanol Fact Book', published by the US Clean Fuels Development Coalition [11], contains assertions such as "Since their introduction in January 1995, 'reformulated' fuels have been a resounding success…", confusing the effects of MTBE and ethanol on air emissions, and 'Because ethanol is inherently cleaner than gasoline, it emits less hydrocarbons, nitrogen oxides, carbon monoxide and hydrogen', oversimplifying the emissions benefits of ethanol, and in the case of NO_x, misrepresenting them entirely. Such omissions of detail and/or lack of technical rigor, whether accidental or deliberate, present the case for ethanol in a more positive light, such that they could mislead both the public and elected decision makers on this issue.

Curiously, the lack of technical rigor also extends to a number of publications in the peer-reviewed and technical literature. For example, a major Australian life cycle assessment comments on the sustainability of E10 with amateurish statements such as [36: p83]: "Ethanol is a renewable fuel. Petrol [gasoline] is a non-renewable fuel. A blend of 10% ethanol will be more sustainable than petrol on its own", presented without evidence, and "There is no evidence of widespread groundwater contamination with petrohol [E10]"—did the authors examine the literature?. A second major Australian study [8] does not even mention groundwater impacts at all, yet claims that "other land, water and biodiversity impacts from the production, distribution and use of 350 ML of biofuels are not significant…" [8:p15]. It goes on to state that "savings in health costs from increased ethanol use of 205 ML are estimated to be A$3.3 million in 2010" [8:p16]—yet it did not take into account health costs associated with contaminated groundwater, nor even the effect of fuel evaporative losses! Similarly, a peer-reviewed article on the Brazilian ethanol program [117] claims that ethanol has an 'almost null greenhouse emissions balance', stated without evidence, and that 'there are no subsidies for ethanol production', again without substantiation, and in direct contradiction to recent economic studies of the Brazilian ethanol industry [101,102]. Such technically inadequate documents do their audience a

great injustice, in that they can distort the decision-making process in a manner which will ultimately rebound on the environment. To ask a rhetorical question: should the policy of ethanol enrichment of gasoline be implemented on the basis of ideology or 'political correctness', because it is 'seen' to be environmentally sound on the basis of rudimentary arguments (assisted by industry lobby groups who stand to make large, protected profits from the policy), or should it be implemented only on the basis of an honest, rigorous technical appraisal of the environmental, human health, economic and political consequences, both positive and negative, without the influence of lobby groups? Even if the policy of ethanol enrichment is preferred, for reasons outside the scope of this review (e.g. energy security or reduction of foreign debt), the decision-makers should have the ability to make an informed decision, knowing the consequences of their actions.

8. Conclusions

This study examines the ethanol enrichment of unleaded gasoline, with specific attention to the following environmental impacts: (1) air pollutant emissions; (2) subsurface impacts; (3) greenhouse gas emissions; (4) energy efficiency and (5) sustainability. Based on detailed literature reviews, it is found that:

- The claimed air pollution benefits of E10 over E0 do not match the evidence in the scientific literature. E10 causes lower tailpipe CO and particulate emissions, but higher acetaldehyde, ethanol and NO_x emissions. Without RVP control, lower hydrocarbon and air toxic tailpipe emissions are negated by higher evaporative losses; whilst all emission benefits may be negated by life cycle losses. There is some case study evidence of a connection between E10 and higher ground ozone levels.
- E10 increases the risk and severity of soil and groundwater contamination, by increasing the risk of tank corrosion, reducing the NAPL-water interfacial tension, increasing contaminant solubility and inhibiting biodegradation. Modeling and case studies indicate that dissolved benzene plumes associated with E10 are 7–150% longer than those produced by E0.
- E10 offers only a marginal (1–5%) reduction in GHG emissions over E0. As a GHG abatement measure, E10 is much less cost-effective than other methods such as afforestation.
- Ethanol has a low to negative NEV over its life cycle (−80 to +40%).
- The sustainability of ethanol production is affected by generous producer and agricultural subsidies; trade barriers; oligarchical concerns; and the need for agricultural expansion (existing feedstocks) and/or genetic engineering (future feedstocks).

The effects are summarized in the schematic diagram in Fig. 2. These findings broadly concur with those of previous reviews of the ethanol in gasoline issue [8,31,36,47,48,69, 72,118], although some studies tend to view ethanol in a more positive light and/or do not adequately consider its detriments, and many do not consider the overall environmental sustainability. Ranking the issues by long-term significance, the oft-claimed

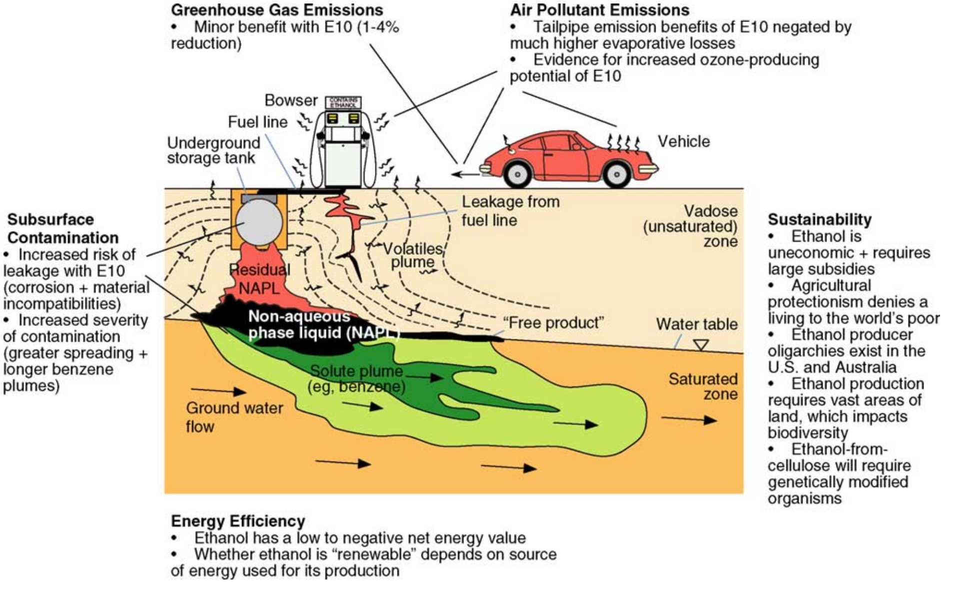

Fig. 2. Schematic representation of the environmental impacts of ethanol in gasoline.

'sustainability' of E10 relative to E0 is brought into question. In contrast, E85 offers substantial GHG benefits but at the expense of significant air pollution, requires tremendous agricultural expansion and/or biotechnological innovation at great risk to biodiversity, and its subsurface contamination impacts are relatively unknown.

Given the present lack of understanding of the environmental impacts of ethanol in gasoline, as well as its political and economic drivers, a great deal more truly independent research (i.e. not funded by or associated with commercial interests) is needed on all aspects of this issue.

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